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Emissions of Naturally Occurring Radioactivity from Aluminum and Copper Facilities

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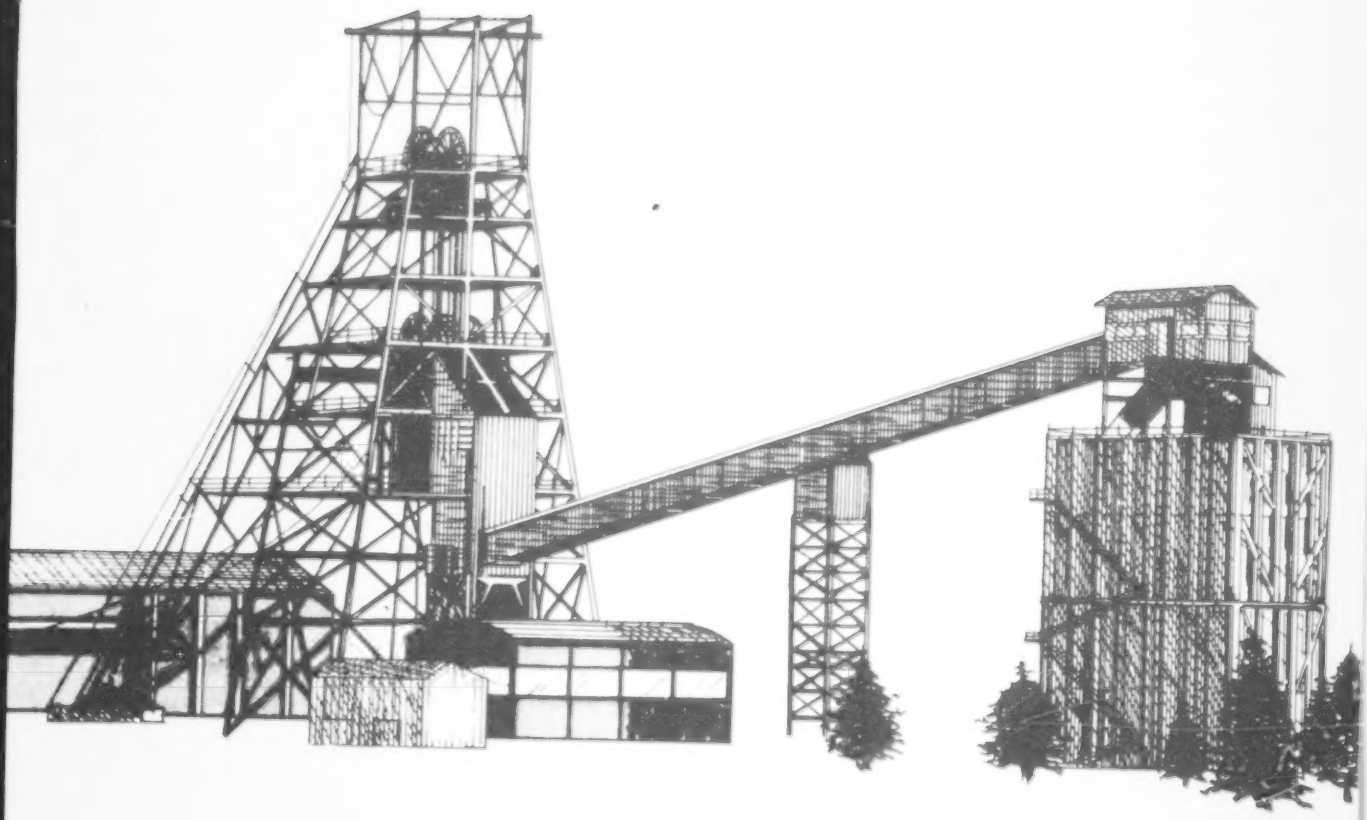

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16. ABSTRACT

This report summarizes five surveys which were conducted at a Bauxite mining operation, an Alumina reduction plant, an Aluminum reduction plant, an underground Copper mine and mill, and an open pit Copper mine and concentrator. Process components and controlled source releases were sampled for naturally occurring radioactivity. Particular emphasis was given to Radon-222, Lead-210, and Polonium-210 emissions from crushing and drying processes.

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EMISSIONS OF NATURALLY OCCURRING RADIOACTIVITY FROM ALUMINUM AND COPPER FACILITIES

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DISCLAIMER

This report has been reviewed by the Office of Radiation Programs-Las Vegas Facility, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FORWARD

The Office of Radiation Programs (ORP) of the U.S. Environmental Protection Agency (EPA) conducts a national program for evaluating exposure of humans to ionizing and nonionizing radiation. The goal of this program is to develop and promote protective controls necessary to ensure the public health and safety.

In response to the 1977 amendments to the Clean Air Act the Las Vegas Facility was given the responsibility to collect field data on emissions to the atmosphere of natural radioactivity from operations involved in the mining, milling, and smelting of minerals other than uranium and coal. This report is one of a series which describes an individual facility and its associated radioactive emissions.

ORP encourages readers of the report to inform the Director, ORP-Las Vegas Facility, of any omissions or errors. Comments or requests for further information are also invited.

Wayne A. Bliss
Acting Director
Office of Radiation Programs-LVF

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Ci	- - curies, 3.7×10^{10} disintegration per second
fCi/m^3	- - femtocuries (10^{-15} curies) per cubic meter
mCi/g	- - millicuries (10^{-3} curie) per gram
nCi/m^3	- - nanocuries (10^{-9} curie) per cubic meter
pCi	- - picocuries, 10^{-12} curies
pCi/g	- - picocuries per gram
pCi/m^2-min	- - picocuries per square meter per minute
TSP	- - total suspended particulates
um	- - micrometer, 10^{-6} meter

SYMBOLS

AMAD	- - activity mean aerodynamic diameter
EIC	- - Eberline Instrument Corporation
GMD	- - geometric mean diameter
GSD	- - geometric standard deviation
HSS	- - Horizontal Stud Soderberg
MSHA	- - Mine Safety and Health Administration

SECTION 1

INTRODUCTION

The Clean Air Act, as amended in August 1977, required the Administrator of the Environmental Protection Agency (EPA) to determine whether emissions of radionuclides into ambient air should be regulated under the Act. In December 1979 the Administrator listed radionuclides as a hazardous pollutant under Section 112 of the Clean Air Act.

The naturally occurring radionuclides most likely to be emitted in significant quantities are those in the uranium-238 and thorium-232 decay series (Figure 1). These radionuclides and their daughter products occur naturally in widely varying amounts in the soils and rocks that make up the earth's crust. Average values for uranium-238 and thorium-232 in soils are approximately 1.8 ppm (0.6 pCi/g) and 9 ppm (1 pCi/g) respectively (1). The radioactivity concentration of each of the daughter products in the two series is approximately equal to that of the uranium-238 or thorium-232 parent.

Almost all operations involving removal and processing of soils and rocks release some of these radionuclides into the air. These releases become potentially important when the materials being handled contain above-average radionuclide concentrations or when processing concentrates the radionuclides significantly above the average amounts in soils and rocks.

Because mining and milling operations involve large quantities of ore, and because there is little information about how these activities release radioactive emissions, EPA, in 1978, began to measure airborne radioactive emissions from various mining, milling, and smelting operations.

Operations were selected for study on the basis of their potential to emit significant quantities of naturally occurring radionuclides to the atmosphere. Some of the factors in the selection included typical mine size, annual U.S. production, measured working levels of radon daughters in underground mines and associated ventilation rates, production rate and process of individual facilities, and previous association with naturally occurring radionuclides. Usually, we chose to look at large facilities in order to improve the chances of obtaining emission samples with radioactivity contents significantly greater than background.

These surveys were screening studies designed to identify potentially important sources of emissions of radionuclides into the air. Any such sources can then be studied in detail to determine whether or not a national emission standard for hazardous pollutants is needed under the Clean Air Act.

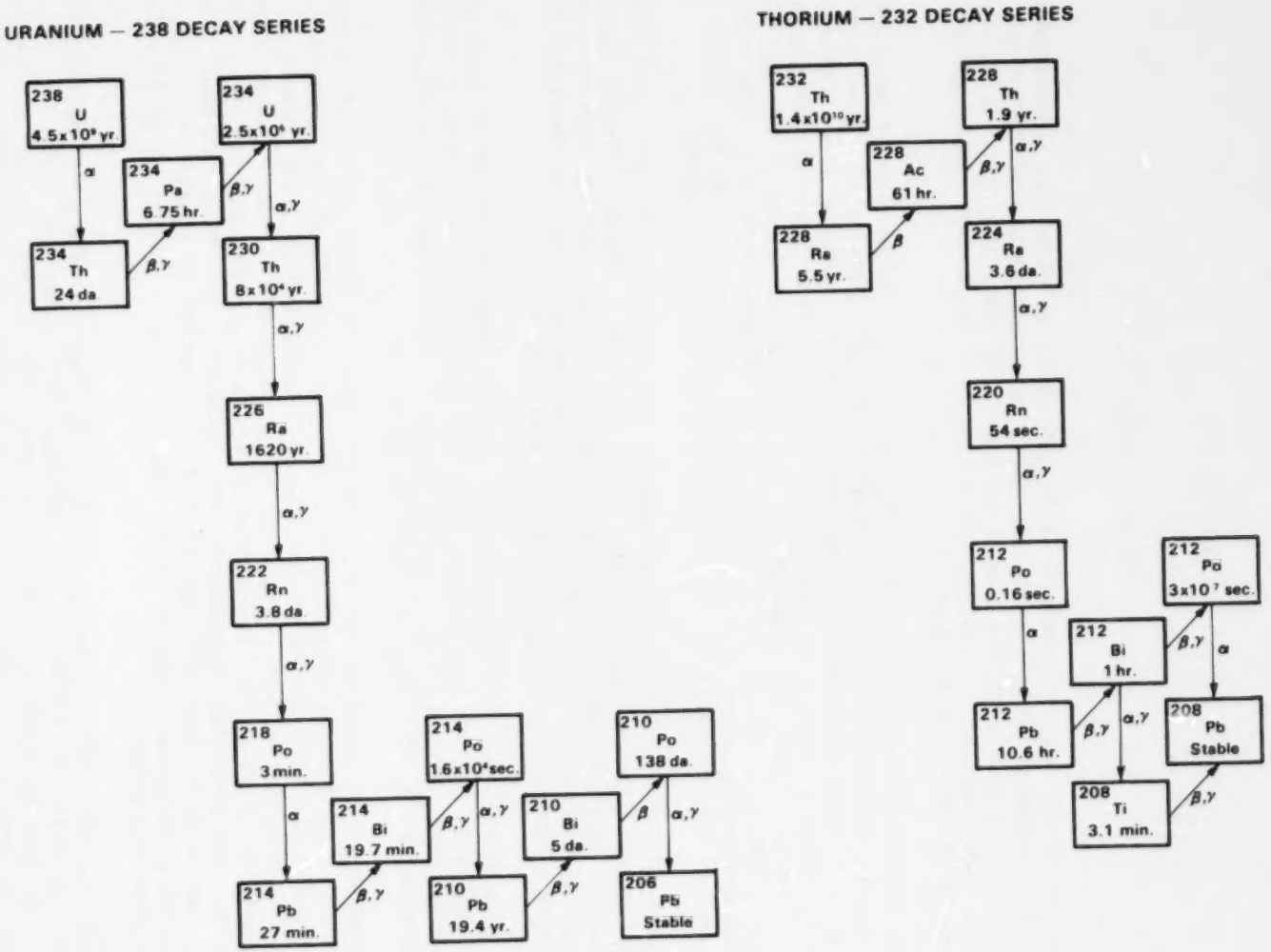

Figure 1. Uranium and thorium radioactivity decay schemes.

SECTION 2

SAMPLE COLLECTION AND ANALYSIS

SAMPLE COLLECTION

Most samples were collected using EPA reference methods (2). Stack sampling points were selected according to EPA Method 1, "Sample and velocity traverses for stationary sources." Stack gas velocity and volumetric flow rate were determined by EPA Method 2, "Determination of stack gas velocity and volumetric flow rate (type S pitot tube)." Gas samples for radon-222 analysis were collected using EPA Method 3, "Gas analysis in carbon dioxide, oxygen, excess air, and dry molecular weight." Total suspended particulates (TSP) in ducts and exhaust stacks were determined using EPA Method 5, "Determination of particulate emissions from stationary sources," or EPA Method 17, "Determination of particulate emissions from stationary sources (in-stack filtrations method)." High volume ambient TSP samples were collected in accordance with the "Reference Method for the Determination of Suspended Particulates in the Atmosphere (3)."

Several contractors performed the sample collection. They used 7.6-cm (3-inch) glass fiber filters for Method 5 samples or 5- by 12.7-cm (2- by 5-inch) glass fiber filters for Method 17 samples. The contractors used 20.3- by 25.4-cm (8- by 10-inch) Microsorban polystyrene fiber filters for ambient TSP samples. Stack and ambient whole air samples for radon analysis were collected in Tedlar bags of 20 to 30 liter capacity.

Generally one set of duplicate radon samples was collected at each sampling point as part of the quality assurance program. When possible, duplicate Method 5 particulate samples were collected from one or two stacks at a given facility.

The contractors collected samples of process materials so that radionuclide emission rates could be compared to the radioactivity of the material handled at that point.

SAMPLE ANALYSIS

The contractors made mass determinations on the various TSP sample fractions before forwarding them for radiological analysis. Eberline Instrument Corporation (EIC) performed the radiological analyses of all samples

except for some duplicate radon samples that were analyzed by EPA in our Las Vegas laboratory as an interlaboratory cross-check.

EIC analyzed process and TSP samples by dissolving the samples and separating the elements of interest by chemical techniques. The separated uranium and thorium fractions were counted on alpha spectrometers for individual isotopic quantitation. An alpha scintillation counter measured the polonium-210. Lead was separated and set aside for about 2 weeks to allow for ingrowth of bismuth-210 from lead-210. After the ingrowth period the bismuth-210 was separated from the lead and was counted on a beta counter to quantitate lead-210. Radium was separated and enclosed as a solution in a sealed tube to allow for ingrowth of radon from radium-226. After three weeks of ingrowth the radon gas was evolved and collected in an alpha scintillation cell to be counted. Stack and ambient gas samples were transferred to alpha scintillation cells and counted for radon.

DATA REPORTING

The radioactivity reported for each sample, except for radon collected on charcoal canisters, is the net radioactivity plus or minus twice the standard deviation (2s). The net radioactivity is the gross sample radioactivity minus the counting equipment background and minus either a) for filter samples, an average value for the radioactivity content of a blank filter, or b) for stack radon samples, the ambient radon concentration. The standard deviation is based only on the random variations inherent in radioactivity counting and is propagated through the various steps to the final result. This random variation, plus the variable radioactivity content of individual filters, occasionally results in a net radioactivity of less then zero. Of course, there is no negative radioactivity. In these cases, as with all others, the net result must be considered along with the standard deviation. Averages of multiple emission samples are given with the standard error of the mean.

SECTION 3

BAUXITE MINE (ALUMINUM INDUSTRY)

PROCESS DESCRIPTION

Bauxites, the principle aluminum ore, are known to have substantially higher levels of uranium and thorium than the parent rock (5). ORP included a domestic bauxite mine as part of this project.

At the survey site, bauxite was mined from open pits which varied in approximate area from 0.3 to 30 hectares. Typical pit dimensions were 40 by 700 m. The mining company conducted pit development by expanding the pit in a direction perpendicular to the long side. Overburden removed by dragline was used to fill the previously mined area which was then reclaimed. Dragline operations were conducted 24 hours per day. The day shift drilled and loaded blasting holes in the ore which were blasted at the end of the shift. The coarsely broken ore was hauled by truck to storage areas or to the alumina plant. The high moisture content of overburden and ore prevented production of airborne particulates during mining operations. Water was applied to haulage roads as necessary to prevent any dust problem.

The area of potential concern regarding radioactivity emissions was radon emanation from the surface of the ore body and overburden piles. Some radon is probably released during blasting, but the ore is generally quite coarse so that release is minimal. Activated charcoal canisters were emplaced on the ore body, exposed faces of overburden, spoils piles, and undisturbed soil.

RESULTS

Radon emanation rates measured are shown in Table 1. The average observed rate of 45 ± 15 pCi/m^2-min from the ore body surface is twice the observed background rate of 22 ± 11. The exposed surface of the ore body is less than that of both the overburden and spoils area. The average radon emanation rate for the entire developed pit area of about 20 pCi/m^2-min is about equal to the background rate for the area.

TABLE 1. BAUXITE PIT RADON EMANATION RATES

Location		Radon Emanation Rate (pCi/m^2-min)[a]
Top of ore body		35
Top of ore body		62
Top of ore body		39
	Average	45 ± 15[b]
Top of overburden - topsoil removed		5.9
Overburden sidewall, 5 ft. below top		13
Overburden sluffage berm, midway between surface and top of ore		2.6
	Average	7.2 ± 5.3
Spoils area		4.9
Spoils area		12
	Average	8.5 ± 5.0
Pit background, undisturbed soil		27
Pit background, undisturbed soil		9.6
Pit background, undisturbed soil		16
Pit background, undisturbed soil		35
	Average	22 ± 11

a) Picocuries (10^{-12} curies) per square meter per minute.

b) Uncertainties of averages are standard deviation about the mean.

SECTION 4

ALUMINA REDUCTION PLANT

PROCESS DESCRIPTION

The alumina reduction plant surveyed used a modified "American Bayer" process to recover alumina (aluminum oxide) from bauxite ore. Red mud, the waste material resulting from this process, is further treated in a lime-sinter process to remove sodium aluminum silicate in the form of pure chemical grade alumina hydrates. The final waste product is referred to as brown mud.

Imported South American ore and domestic ore are blended and used as described above. Imported Jamaican ore is used separately and is treated only by the Bayer process. In the Bayer process ore is wet ground in rod mills. The resulting slurry passes through a digestion process to dissolve the alumina in caustic liquor which is separated from the red mud. Alumina trihydrate is precipitated from the liquor, washed, filtered, and calcined at 1150°C (2100°F) in rotary kilns to produce alumina, which may be shipped as is or may receive further chemical processing for metallurgical and chemical alumina uses.

Red mud from the Bayer process is filtered and reslurried with the addition of limestone and soda ash, then is ball milled. The milled slurry is sintered at 1260°C (2300°F) in rotary kilns. Sinter is ball milled with water to dissolve sodium aluminate formed during sintering. After purification the sodium aluminate liquor is routed to precipitators for recovery of chemical grade hydrates.

Radon present in the ore is presumed to be lost to the atmosphere during the milling and digestion processes. No single source of emission exists to sample such emissions. Radon concentrations were measured in the exhausts of the Bayer process, alumina hydrate vacuum filter, rotary kiln, and red mud vacuum filter. Also radon was measured in exhausts from the lime-soda process, lime and sinter kilns, and in natural gas fuel to alumina and sinter kilns. Radon emanation from the brown mud tailings area was measured with charcoal canisters.

TSP and size-fractionated particulate samples were collected from the alumina kiln electrostatic precipitator inlet and exhaust and from the red mud kiln exhaust.

Process samples included domestic ore from the mine pit surveyed, blended bauxite, alumina kiln feed, alumina product, chemically treated alumina product

TABLE 2. RADIOACTIVITY IN ALUMINA PLANT PROCESS SAMPLES

Sample	Radioactivity Concentrations (pCi/g)[a]							
	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Bauxite Ore	6.8 ± 0.7	6.9 ± 0.7	6.4 ± 1.1	7.4 ± 2.2	9.1 ± 1.1	10.0 ± 1	5.5 ± 1.0	5.5 ± 1.0
Blended Bauxite	4.0 ± 0.5	4.0 ± 0.5	3.5 ± 0.3	4.4 ± 1.3	5.3 ± 0.4	4.2 ± 0.5	5.2 ± 1.2	5.6 ± 1.2
Alumina Kiln Feed	0.05 ± 0.03	0.07 ± 0.03	<0.05	0.08 ± 0.05	0.20 ± 0.15	0.00 ± 0.20	<0.05	<0.05
Alumina Product	0.28 ± 0.10	0.28 ± 0.10	<1	0.23 ± 0.07	<1.4	<0.6	<0.2	<0.2
RC-64 Alumina	0.31 ± 0.09	0.35 ± 0.10	<0.6	0.19 ± 0.06	<1.3	<0.6	<0.2	<0.2
Red Mud Filter Cake	7.5 ± 1.2	7.5 ± 1.2	5.1 ± 1.3	6.5 ± 2.0	7.6 ± 0.4	7.7 ± 1.7	6.0 ± 1.5	6.3 ± 1.5
Prepared Sinter Mud	4.8 ± 0.5	4.7 ± 0.5	4.2 ± 1.1	3.9 ± 1.2	6.8 ± 0.4	4.6 ± 0.5	5.0 ± 1.3	5.5 ± 1.4
Sinter	6.4 ± 0.8	6.6 ± 0.9	6.5 ± 1.6	3.9 ± 1.2	3.6 ± 0.4	3.2 ± 1.2	9.2 ± 2.1	8.6 ± 2.0
Brown Mud[b]	5.5 ± 0.4	5.6 ± 0.5	8.0 ± 2.7	5.6 ± 1.2	5.7 ± 0.8	5.4 ± 0.7	12.5 ± 4	12.5 ± 4

a) Picocuries (10^{-12} curies) per gram plus or minus twice the standard deviation based on counting statistics.

b) The results are derived from duplicate samples.

(RC-64), red mud filter cake, prepared sinter mud, sinter, and brown mud tailings.

RESULTS

As shown in Table 2, the bauxite ore was elevated in both uranium-238 and thorium-232 with concentrations of 6.8 and 5.5 pCi/g. The addition of imported ore reduced the concentration of uranium to 4.0 pCi/g. Removal of alumina, which contained only 0.05 pCi/g of uranium-238 and less than 0.05 pCi/g of thorium-232 resulted in increasing the concentrations in red mud. The uranium and thorium concentrations were again diluted by the addition of lime and soda ash to about 5 pCi/g. The first fractionation of radioactivity occurred in the sinter kiln where lead-210 and polonium-210 were reduced to about half the concentration of the precursors. The brown mud lake tailings results, collected from the vicinity of the charcoal canisters, shows that the lead-210 to be in approximate equilibrium with its precursors and polonium-210 to be in equilibrium with lead-210. Lead-210 in the other process samples appears to be biased high, relative to uranium and the same bias probably applies here as well. Because of the age of the tailings sample the polonium-210 would have grown to some higher degree of equilibrium than in the sinter material.

The low radioactivity of alumina is reflected in the radioactivity emissions from the alumina kilns (Table 3). Even though kiln 4 was found to be emitting about 20 times as much mass as usual, probably due to an inoperative electrostatic precipitator, the estimated annual release for the four kilns operating during the survey was 0.068 mCi/y for uranium-238 and -234 and <0.055 mCi/y for radium-226.

TABLE 3. ALUMINA PLANT PARTICULATE RADIOACTIVITY EMISSION RATES

Source	Radionuclides (mCi/y)[a]							
	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Hood System 1	<0.7	<1.0	<2.0	<0.4	8.1	<6.0	<2	<2
Hood System 3	<2.0	<0.7	<2.0	<0.3	7.8	7.5	<1	<1
Stacks[b]	<6.0	<4.0	<3.0	<2.0	32.0	<27	<6	<6

a) Estimated from Method 5 contractor results
b) Four stack total

Emissions of radionuclides from the red mud sinter kiln were below measurable concentrations except for lead-210 and polonium-210. The high temperatures caused a large fraction of those to be volatilized, as shown by the process sample results. Emissions of the two nuclides were essentially equal with 7.8 mCi/yr for lead-210 and 9.3 mCi/yr for polonium-210.

TABLE 4. ALUMINA PLANT AMBIENT AND STACK RADON-222 MEASUREMENTS

Source	Collected Time	Collected Date	Concentrations (nCi/m^3)[a] Gross	Concentrations (nCi/m^3)[a] Net	Annual Emissions (Ci/Yr)
Ambient Air	1252-1650	11/13/79	0.13 ± 0.04		
	0955-1417	11/14/79[b]	0.16 ± 0.03		
	0941-1332	11/15/79	0.45 ± 0.08		
Alumina	1319-1618	11/13/79	0.07 ± 0.03	-0.06 ± 0.05	
Alumina	1009-1358	11/14/79[b]	0.25 ± 0.04	0.09 ± 0.05	
	0956-1301	11/15/79	0.29 ± 0.07	-0.16 ± 0.11	
	Source Average			-0.04 ± 0.18	
Alumina	1315-1606	11/13/79	0.49 ± 0.07	0.36 ± 0.08	
	0925-1230	11/14/79	0.50 ± 0.06	0.34 ± 0.08	
	1013-1332	11/15/79[b]	0.52 ± 0.05	0.07 ± 0.09	
	Source Average			0.26 ± 0.16	0.074
Alumina	1314-1621	11/13/79[b]	0.53 ± 0.05	0.40 ± 0.06	
	1337-1345	11/14/79	0.47 ± 0.06	0.31 ± 0.08	
	1010-1322	11/15/79	0.55 ± 0.11	0.10 ± 0.14	
	Source Average			0.27 ± 0.15	0.067
	Total for 4 Kilns				0.27
Red Mud	1145-1611	11/13/79	1.5 ± 0.1	1.4 ± 0.1	
	0941-1338	11/14/79[b]	2.1 ± 0.1	1.9 ± 0.1	
	0943-11/15/79		1.5 ± 0.1	1.0 ± 0.1	
	Source Average			1.4 ± 0.5	0.019

TABLE 4. (Continued)

Source	Collected Time	Collected Date	Concentrations (nCi/m^3)[a] Gross	Concentrations (nCi/m^3)[a] Net	Annual Emissions (Ci/Yr)
Lime Kiln	1216-1552	11/13/79	0.03 ± 0.01	-0.13 ± 0.04	
Red Mud	1228-1606	11/13/79[b]	1.2 ± 0.1	1.1 ± 0.1	
	0930-1331	11/14/79	1/3 ± 0.1	1.1 ± 0.1	
	0930-1320	11/15/79	1.7 ± 0.1	1.2 ± 0.1	
	Source Average			1.1 ± 0.1	0.39
Total for 5 kilns					2.0
Natural Gas	1515	11/15/79[b]	5.8 ± 0.1		

a) Nanocuries (10^{-9} curies) per dry, standard cubic meter (20°C, 760 mm mercury pressure) plus or minus twice the standard deviation based either on counting statistics or in the case of source averages on sample variance..

b) The results are derived from duplicate samples.

Two size-fractionated particulate samples were collected from the alumina kiln 8 stack and from the sinter kiln stack. Radioactivity was below detectable levels on the size fractions collected from the alumina kiln, but the mass distribution by aerodynamic particle size for the two samples showed a geometric mean diameter (GMD) of 2.2 μm with a geometric standard deviation (GSD) of 2.4 on one sample and a GMD of 3.3 μm with a GSD of 2.8 on the other. The sinter kiln aerodynamic size distribution was a GMD of 2.3 μm and GSD of 3.9 on one sample and a GMD of 2.4 μm and GSD of 3.8 on the other. Radioactivity levels on the first sinter kiln sample, analyzed by individual stages were below detectable. Compositing of stages from the second sample resulted in detectable quantities of polonium-210 being measured. Polonium-210 activity mean aerodynamic diameter (AMAD) was 5.5 μm with a GSD of 8.1. This result was the opposite of the expected AMAD of less than 1 μm and low GSD.

The highest average radon concentration in a stack was measured on the discharge from the red mud vacuum filter at 1.4 ± 0.5 nCi/m^3 (Table 4). With a low exhaust flow rate it emitted only 0.019 Ci/y. The largest process source of radon-222 was the red mud sinter kiln with a single kiln emission rate of 0.39 Ci/y. Total for the five kilns operating at that time was 2.0 Ci/y. The alumina kiln emissions averaged .074 Ci/y from kiln 4 and .067 Ci/y from kiln 8 with an average for four operating kilns of .27 Ci/y. It is probable, considering the low radioactivity of alumina and the negative result for the discharge rate of radon-222 from the alumina vacuum filter, that the alumina kiln emission was due to radon-222 in the natural gas fuel. Natural gas was found to have a radon-222 concentration of 5.8 ± 0.1 nCi/m^3.

Charcoal canister radon-222 emanation measurements from the brown mud tailings lake and an undisturbed area nearby are shown in Table 5. The overlapping confidence intervals rule out any finding of a significant difference between the emanation rate averages.

TABLE 5. BROWN MUD TAILINGS RADON EMANATION RATES

	Emanation Rates (pCi/m^2-min)[a]	
	Tailings	Background
	67	21
	33	40
	43	26
	48	5
	15	
	11	
	19	
Average[b]	34 ± 20	23 ± 14

a) Picocuries (10^{-12} curies) per square meter per minute.
b) Average plus or minus the standard deviation about the mean.

SECTION 5

ALUMINUM REDUCTION PLANT

PROCESS DESCRIPTION

Aluminum metal is produced from alumina by the "Hall" electrolytic reduction process. An electric current passed through a large shallow pot of cryolite (Na_3AlF_6) raises the temperature to about 975°C, which maintains the cryolite in a molten state. Alumina, in a fine powder form, is periodically added to the surface of the molten cryolite which serves as both an electrolyte and solvent for the alumina. Small amounts of aluminum fluoride are added to maintain the optimum level of fluoride which is lost in the pot emissions.

A carbon lining in the pot serves as the cathode and a carbon anode is immersed in the molten cryolite from above the pot. Two forms of anode are used, either prebaked anodes consisting of large blocks of petroleum coke or an asphalt pitch binder which is baked to a hard carbon. These are replaced as the anodes are consumed by the oxygen released in the alumina reduction process. Horizontal Stud Soderberg (HSS) anodes use a process in which a coke-pitch mixture is placed in a hopper atop the pot. Horizontal metal studs, which also serve as the electrical connection, are inserted into the mass above the molten surface. The high temperature of the pot bakes the mixture into a solid carbon mass as it nears the pot. The studs are periodically withdrawn and inserted higher to allow the anode to descend as it is consumed.

Several processes, including materials handling and electrode preparation, produce atmospheric emissions of vapors and particulates which were not considered to be significant sources of radioactivity. The only sources of concern to this survey were the controlled and uncontrolled emissions from the reduction pots. Reduction pot operation is essentially an open process, but hoods are employed to control emissions. Several techniques for hooding the pots were being evaluated to determine the optimum for each pot type. Wet scrubbers treat the fumes collected from groups of 40 pots before discharging the exhaust to the atmosphere through 36 m stacks. Eighty pots in each of two buildings comprise the pot line. Each building, approximately 350 m long, is ventilated by natural circulation through roof ridgeline monitors. The combinations of winds and thermal rise from the hot pots produces a reported ventilation rate of one air change every minute or two.

TABLE 6. RADIOACTIVITY ALUMINUM REDUCTION PLANT PROCESS SAMPLES

Sample		Radioactivity Concentrations (pCi/g)[a]							
		U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Alumina		0.08 ± 0.05	0.11 ± 0.06	<0.2	0.20 ± 0.06	<1.4	<0.7	<0.2	<0.2
Alumina		0.12 ± 0.06	0.13 ± 0.06	<0.2	0.14 ± 0.04	<1.6	<0.7	<0.2	<0.2
	Average[b]	0.10 ± 0.04	0.12 ± 0.04	<0.2	0.17 ± 0.04	<1.5	<0.7	<0.2	<0.2
Aluminum Fluoride		0.13 ± 0.05	0.26 ± 0.08	<0.2	0.12 ± 0.04	<1.5	<0.7	<0.2	<0.2
Aluminum Fluoride		0.08 ± 0.05	0.13 ± 0.06	<0.2	0.12 ± 0.04	<1.4	<0.7	<0.2	<0.2
	Average[b]	0.11 ± 0.04	0.20 ± 0.05	<0.2	0.12 ± 0.03	<1.5	<0.7	<0.2	<0.2
Cryolite		0.11 ± 0.06	0.12 ± 0.06	<0.2	0.15 ± 0.04	<1.6	<0.7	<0.2	>0.2
Cryolite			0.09 ± 0.05	<0.2	0.12 ± 0.04	<1.6	<0.7	<0.2	>0.2
	Average[b]	0.11 ± 0.06	0.11 ± 0.04	<0.2	0.14 ± 0.03	<1.6	<0.7	<0.2	<0.2
Aluminum		0.04 ± 0.03	0.09 ± 0.05	<0.2	0.15 ± 0.04	<1.5	<0.7	<0.2	<0.2
Aluminum		0.15 ± 0.06	0.10 ± 0.05	<0.2	0.14 ± 0.04	<1.6	<0.7	<0.2	<0.2
	Average[b]	0.10 ± 0.03	0.10 ± 0.04	<0.2	0.15 ± 0.03	<1.6	<0.7	>0.2	>0.2

a) Picocuries (10^{-12} curies) per gram plus or minus twice the standard deviation based on counting statistics.

b) Picocuries per gram plus or minus the standard deviation based on sample variance.

RESULTS

Two exhaust stacks were sampled. One handled emissions from 40 HSS pots and one handled emissions from 20 HSS pots and 20 prebake pots. High volume air samplers collected particulate emissions from the roof monitors over each building. Radon was measured in the stack emissions and at the roof monitors.

The company provided samples of alumina, aluminum fluoride, cryolite, and aluminum. All materials exhibited similar radioactivity concentrations, averaging 0.13 pCi/g for those uranium chain nuclides which were present in detectable quantities (Table 6).

Radon-222 in stack emissions and building ventilation air was found to be indistinguishable from ambient levels.

Only lead-210 and polonium-210 were collected from the hooding system exhaust stacks in measurable quantity. Lead-210 emissions averaged 8.1 mCi/y in hooding system 1 and 7.8 mCi/y in hooding system 3 (Table 7). The total from the four stacks was 32 mCi/y. Polonium-210 averaged <6 mCi/y from hooding system 1 and 7.5 from hooding system 3, with a four-stack total of 27 mCi/y. The total emissions of the other particulate radionuclides averaged <8 mCi/y.

TABLE 7. ALUMINUM REDUCTION PLANT EMISSION RATE

	Radionuclides (mCi/y)[a]							
Source	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Alumina Kilns[b]	0.068	0.068	<0.24	<0.055	<0.34	<0.14	<0.05	<0.05
Red Mud Sinter Kilns[c]					7.8	9.3		

a) Estimate from Method 5 contractor results.
b) Total emissions from four kilns
c) Total emissions from six kilns

Lead-210 and polonium-210 were collected in measurable quantities on the high volume filter samples collected from the roof monitor of the north pot room. No measurable quantities of any radionuclides were collected from the south building roof monitor. Roof access limited sampling to the south side of the north building roof monitor and to the north side of the south building roof monitor. Wind directions may have influenced the flow of particulates through the monitors, but mass loading on the south building samples were higher than on the north building samples. Concentrations measured in the north building roof monitor were: lead-210, 8 ± 220 fCi/m^3; polonium-210, 200 ± 250 fCi/m^3. The concentrations measured the following day were: lead-210, 60 ± 130 fCi/m^3; polonium-210, 550 ± 210 fCi/m^3. The relatively high uncertainties associated with the net concentrations result from the relatively large and variable blank filter analyses. These compare to ambient

concentrations measured near the plant of: lead-210, 16 ± 6 fCi/m^3; polonium-210, 17 ± 6 fCi/m^3. The average lead-210 emission concentration of 16 ± 6 fCi/m^3; polonium-210, 17 ± 6 fCi/m^3. The average lead-210 emission concentration of 33 ± 26 fCi/m^3 did not differ significantly from ambient. The average polonium-210 concentration of 380 ± 180 was significantly higher than ambient. Assuming one air change every 2 minutes the annual emissions of polonium-210 from the building, based on the two samples, would be 17 mCi.

SECTION 6

UNDERGROUND COPPER MINE AND MILL

PROCESS DESCRIPTION

Selected for this survey was an underground copper-iron-zinc-sulfide mine. The Mine Safety and Health Administration (MSHA) had reported average radon daughter WL* measurements of 0.087 with a maximum of 0.21. (personal communication with Aurél Goodwin, MSHA). The ore runs less than 1 percent copper, less than 1 percent zinc, 20 percent iron, and 25 percent sulfur. A mill and flotation plant produces concentrates of the three sulfides and disposes of about 50 percent of the ore as tailings.

The mine operates three shifts per day, 5 days per week. Blasting of the drilled ore is done at about 1500 hours each day. An exhaust fan housed above a vertical shaft into the mine provides a ventilation rate of 2,660 m^3-min through the mine. Air discharge is horizontal at ground level through a 1.76-m diameter outlet.

Ore from the mine surveyed, from another adjacent underground mine, and an adjacent open pit mine is processed in the flotation plant. Primary and secondary crushers reduce the ore to less than 2-inch size before it enters the ball mills of the flotation plant. A rotoclone wet scrubber cleans the emissions from the crushers. The scrubber discharges horizontally about 4 m above ground at 484 m^3-min. The mill produces about 15,000 tons each of copper and zinc and 300,000 tons of iron as sulfides per year.

As shown in Table 8, the uranium decay chain nuclides were at or slightly above the average concentrations found in crustal rock. The ore concentration averaged about 1 pCi/g.

As would be expected in a process which is designed to selectively concentrate metals, the concentrates generally have lower radionuclide concentrations than the ore or tailings. The zinc concentrating process seems to be the most discriminating with concentrations averaging 40 percent of those in ore.

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* Working Level (WL) is defined as any combination of short lived radon daughter products in one liter of air that will result in the ultimate emission of 1.3 x 10^5 Mev of potential alpha energy (U.S. Public Health Service publication No. 494, 1957).

TABLE 8. UNDERGROUND COPPER MINE AND MILL PROCESS SAMPLE RADIOACTIVITY

Sample		Radioactivity Concentrations (pCi/g)[a]							
		U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Ore		0.79 ± 0.14	0.72 ± 0.13	0.92 ± 0.60	0.33 ± 0.20	0.80 ± 0.43	0.73 ± 0.39	0.53 ± 0.46	0.36 ± 0.31
		0.78 ± 0.19	0.93 ± 0.22	1.6 ± 0.4	1.4 ± 0.4	2.1 ± 2.0	2.0 ± 1.9	0.46 ± 0.17	0.44 ± 0.16
		0.79 ± 0.20	0.80 ± 0.20	1.5 ± 0.9	0.69 ± 0.21	1.1 ± 0.4	1.0 ± 0.4	0.88 ± 0.61	0.88 ± 0.61
	Average[b]	0.79 ± 0.10	0.82 ± 0.11	1.3 ± 0.4	0.81 ± 0.16	1.3 ± 0.7	1.2 ± 0.7	0.62 ± 0.26	0.56 ± 0.23
Copper Concentrate		0.63 ± 0.14	0.63 ± 0.15	0.73 ± 0.21	0.84 ± 0.25	0.84 ± 0.64	0.76 ± 0.58	0.04 ± 0.04	0.04 ± 0.04
		0.59 ± 0.15	0.57 ± 0.16	0.87 ± 0.29	0.99 ± 0.30	0.41 ± 0.29	0.41 ± 0.29	0.14 ± 0.09	0.13 ± 0.09
		0.73 ± 0.17	0.78 ± 0.18	0.98 ± 0.34	0.77 ± 0.23	0.44 ± 0.27	0.41 ± 0.25	0.04 ± 0.05	0.04 ± 0.05
	Average[b]	0.65 ± 0.09	0.66 ± 0.09	0.86 ± 0.16	0.87 ± 0.15	0.56 ± 0.25	0.53 ± 0.23	0.07 ± 0.04	0.07 ± 0.04
Zinc Concentrate		0.28 ± 0.07	0.33 ± 0.08	0.52 ± 0.24	0.17 ± 0.05	0.45 ± 0.22	0.41 ± 0.20	0.10 ± 0.09	0.07 ± 0.06
		0.29 ± 0.07	0.36 ± 0.08	0.42 ± 0.18	0.44 ± 0.13	0.52 ± 0.32	0.48 ± 0.29	-0.01 ± 0.03	0.18 ± 0.09
		0.37 ± 0.09	0.41 ± 0.10	0.34 ± 0.18	0.40 ± 0.12	0.67 ± 0.28	0.62 ± 0.26	-0.18 ± 0.12	-0.18 ± 0.12
	Average[b]	0.31 ± 0.04	0.37 ± 0.05	0.43 ± 0.12	0.34 ± 0.06	0.55 ± 0.16	0.50 ± 0.15	-0.03 ± 0.05	0.02 ± 0.05
Iron Concentrate		0.37 ± 0.11	0.38 ± 0.11	0.44 ± 0.30	0.10 ± 0.06	0.8 ± 1.8	0.8 ± 1.6	0.10 ± 0.12	0.10 ± 0.12
		0.42 ± 0.10	0.47 ± 0.10	0.72 ± 0.18	0.86 ± 0.26	0.60 ± 0.36	0.55 ± 0.33	0.09 ± 0.05	0.09 ± 0.05
		0.52 ± 0.12	0.51 ± 0.12	0.94 ± 0.26	0.52 ± 0.16	0.86 ± 0.75	0.80 ± 0.70	0.37 ± 0.14	0.37 ± 0.14
	Average[b]	0.44 ± 0.06	0.45 ± 0.06	0.70 ± 0.15	0.49 ± 0.10	0.75 ± 0.66	0.72 ± 0.59	0.19 ± 0.06	0.19 ± 0.06
Tailings		0.86 ± 0.16	0.79 ± 0.15	0.86 ± 0.22	0.76 ± 0.23	1.3 ± 0.7	1.2 ± 0.7	0.19 ± 0.8	0.19 ± 0.08
		0.88 ± 0.18	0.84 ± 0.16	1.1 ± 0.2	1.4 ± 0.4	1.2 ± 0.9	1.1 ± 0.8	0.23 ± 0.09	0.22 ± 0.09
		0.71 ± 0.12	0.77 ± 0.13	1.3 ± 0.2	0.41 ± 0.12	0.97 ± 0.58	0.90 ± 0.54	0.29 ± 0.06	0.25 ± 0.06
	Average[b]	0.82 ± 0.09	0.80 ± 0.08	1.1 ± 0.1	0.86 ± 0.16	1.2 ± 0.4	1.1 ± 0.4	0.24 ± 0.27	0.22 ± 0.04

a) Picocuries (10^{-12} curies) per gram plus or minus twice the standard deviation based on counting statistics.

b) Picocuries per gram plus or minus the standard deviation based on sample variance.

TABLE 9. UNDERGROUND COPPER MINE AND MILL RADON-222 MEASUREMENTS

Source	Collected Time	Collected Date	Concentrations (nCi/m^3)[a] Gross	Concentrations (nCi/m^3)[a] Net	Annual Emissions (Ci/Yr)
Ambient Air	1000-1400	1/30/79	0.64 ± 0.28		
	1600-1835	1/30/79	0.40 ± 0.16		
	2300-0215	1/31-2/01	0.14 ± 0.20		
	0940-1200	2/01/79	-0.01 ± 0.14		
	1202-1350	2/01/79	-0.03 ± 0.20		
Crusher	1625-1720	1/30/79	0.26 ± 0.14		
	1500-1700	2/01/79[b]	0.02 ± 0.13		
Mine Outlet	1230-1500	1/30/79	4.6 ± 0.2	4.0 ± 0.3	
	1530-1800	1/30/79	6.0 ± 0.4	5.6 ± 0.4	
	2305-0235	1/31-2/01	4.0 ± 0.2	3.9 ± 0.3	
	0950-1210	2/01/79	5.4 ± 0.4	5.4 ± 0.4	
	1212-1400	2/01/79	2.8 ± 0.4	2.8 ± 0.4	
	1410-1630	2/01/79	4.8 ± 0.4	4.8 ± 0.4	
	Mine Outlet Average			4.4 ± 1.1	6.2
Crusher	1626-1720	1/30/79	0.68 ± 0.16	0.42 ± 0.23	
	1500-1700	2/01/79	1.8 ± 0.2	1.8 ± 0.3	
	Crusher Exhaust Average			1.1 ± 1.0	0.28

a) Nanocuries (10^{-9} curies) per cubic meter plus or minus twice the standard deviation based on counting for individual sample results; plus or minus the standard deviation of the mean for source averages.

b) The results are derived from duplicate samples.

RESULTS

Ambient radon concentrations measured near the facility and discharges from the mine and the mill crusher are shown in Table 9. During the latter part of the survey, snow-cover apparently reduced the ambient radon concentration by reducing radon emanation from soil. Radon concentrations in mine exhaust air averaged 4.4 ± 1.0 nCi/m^3 with an annual estimated emission of 6.2 Curies. Some disagreement exists between the MSHA WL measurements and EPA radon measurements in the mine exhaust. The MSHA reported an average of 0.087 WL would require a radon concentration of 8.7 nCi/m^3 at 100 percent equilibrium. One or both sets of measurements may be biased, or mine operations may have changed.

Radon in the crusher exhaust averaged 1.1 ± 1.0 nCi/m^3 above ambient levels, with a net annual emission of 0.28 curies.

Radioactivity in suspended particulates in the crusher exhaust were not significantly greater than zero. Annual emissions of individual uranium chain radionuclides were each less than 6 μCi.

SECTION 7

OPEN PIT COPPER MINE AND CONCENTRATOR

PROCESS DESCRIPTION

A large open-pit copper mine and the associated mill and concentrating plant were surveyed to further characterize the copper industry radioactivity emissions. At the time of the survey the pit covered an area of about 2250 by 1700 m and had reached a depth of about 550 m. The mine operators removed about 158,000 MT of material per day, of which about 45,300 MT were ore.

Ore and rock were blasted each day at noon. Ore trucks operated around the clock hauling ore to the crusher or leach screening pile and rock to the waste dump. Ore which graded 0.24 percent copper or higher was sent to the crusher. That which graded 0.10 to 0.23 percent went to the leach screening pile where copper was chemically leached from the ore. Rock grading less than 0.10 percent was waste rock. A baghouse controlled particulate emissions at the crusher and truck hopper. Vibrating grizzly feeders screened the crushed ore at 4 inches. Oversize is sent to a gyratory primary crusher. Undersize and crushed ore were moved by conveyor belt to an open coarse ore stockpile or to six coarse ore storage bins. "Chem-Jet" sprays were used to suppress dust formation after the grizzlies, at the entrance to the primary crusher, and at the crusher discharge. A baghouse identical to the one on the truck hopper collected dust from all primary crusher operations.

"Chem-Jet" sprays and hoods connected to the baghouse controlled dust from transfer points on the conveyor from the primary crusher to storage. Similar controls collected dust from transfer and discharge points on the conveyor system from coarse ore storage to six surge bins at the secondary crusher.

Vibrating screens separated ore from the surge bins at 1 inch (2.5 cm) with undersize going directly to 12 fine ore storage bins at the concentrator building. Oversize was crushed to 3/4-inch (2-cm) size in three gyratory crushers and sent to fine ore storage. Transfer points were hooded and the dust was collected by six Ducon wet scrubbers. Chem-Jet spray systems also controlled dust at belt transfer points.

A system of belts carried ore from the 12 fine ore bins to six rod mills. Twelve ball mills, operating in a closed circuit, further ground the ore from the rod mills. A cyclone and flotation section recovered mineral values from the pulverized ore. Sand tailings were thickened and pumped 4.8 km (3 miles) to the tailings pond. Wet concentrates were carried by rail to the smelter. Seven Ducon scrubbers collected dust from the fine ore bins area. Roof fans, a

wall fan, and natural ventilation provided ventilation for the concentrator building. The entire process of milling, flotation, and concentration was carried on under one roof. The process was wet and generated no appreciable airborne particulates. Water decanted from the tailings pond was recycled to be used as flotation spray water.

SAMPLING POINTS

Ambient suspended particulate and radon samples were collected at three locations around the facility. One ambient site, identified as Mountain Con was about 0.8 km northwest of the mine pit, 2.9 km northwest of the concentrator. The second site, Alpine, was about 270 m southeast of the concentrator building and 1.9 km southeast of the mine center. The third site, Kaw Avenue, was about 2.4 km southwest of the mine pit and concentrator. Continuous 24-hour high volume particulate samples were collected simultaneously with all plant emission radon samples. Sufficient samples were collected to assure at least two samples from each 4-hour period of the day. Measurements of radon emanation from the surface were made in the mine pit and from surrounding areas by charcoal canisters.

TSP and size-fractionated particulate emission samples were collected from the truck hopper and primary crusher exhausts. Company data and visual examination indicated that other possible controlled sources would be insignificant compared to those two.

Emissions of radon were measured from the truck hopper, primary crusher, secondary crusher, and concentrator handling exhausts.

Size-fractionated suspended particulate samples were collected adjacent to the coarse ore storage pile and the leach screening pile.

SAMPLE RESULTS

Radioactivity concentrations in ore, concentrates, and tailings are shown in Table 10. Concentrations in ore of uranium and thorium chain nuclides are about three times the average expected in crustal rock. As in the mill process associated with the underground copper mine, the radioactivity levels in copper concentrate are consistently lower than in ore, but the individual results are not significantly different.

Radon concentrations measured at the three ambient stations are shown in Table 11. Hourly average wind directions were evaluated to determine if the station had been upwind, downwind, or crosswind from the open mine pit during each sampling period. In only three cases was it determined that a station had been downwind. Although diurnal variations are quite evident, with the highest concentrations during the early morning hours and lowest concentrations during the afternoon, no effect was observed as a result of being upwind or downwind of the mine.

TABLE 10. OPEN PIT COPPER MINE AND CONCENTRATOR PROCESS SAMPLE RADIOACTIVITY

Sample	Radioactivity Concentrations (pCi/g)[a]							
	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Ore-Primary Crusher	2.4 ± 0.3	2.2 ± 0.3	3.6 ± 0.9	0.92 ± 0.28	7.2 ± 2.7	6.3 ± 1.6	2.5 ± 0.7	3.5 ± 1.2
	2.0 ± 0.4	1.9 ± 0.4	6.7 ± 1.7	1.5 ± 0.4	4.7 ± 1.5	5.0 ± 1.5	4.2 ± 1.2	4.5 ± 1.4
Ore-Secondary Crusher	2.2 ± 0.5	2.2 ± 0.5	3.8 ± 1.4	0.42 ± 0.13	2.6 ± 1.3	3.5 ± 1.3	3.5 ± 1.0	3.8 ± 1.2
	2.0 ± 0.3	1.4 ± 0.2	2.4 ± 0.8	0.72 ± 0.21	2.0 ± 1.3	3.3 ± 1.3	2.0 ± 0.7	1.5 ± 0.6
Ore Average	2.2 ± 0.3	1.9 ± 0.3	4.1 ± 0.8	0.89 ± 0.12	4.1 ± 0.9	4.5 ± 0.9	3.1 ± 0.6	3.3 ± 0.7
Concentrate	1.1 ± 0.3	1.2 ± 0.3	2.0 ± 0.8	0.14 ± 0.04	<2.3	<1.2	1.3 ± 0.6	0.94 ± 0.40
	1.7 ± 0.4	1.6 ± 0.3	3.4 ± 1.1	0.93 ± 0.28	2.6 ± 1.5	2.2 ± 1.1	0.82 ± 0.46	1.0 ± 0.4
Concentrate Average	1.4 ± 0.3	1.4 ± 0.2	2.7 ± 0.7	0.54 ± 0.14	<2.5	<1.7	1.1 ± 0.4	0.97 ± 0.3
Tailings	1.5 ± 0.3	1.5 ± 0.3	3.2 ± 1.4	1.0 ± 0.3	2.1 ± 1.4	2.0 ± 1.1	3.7 ± 1.6	4.9 ± 1.5
	1.7 ± 0.3	1.5 ± 0.3	4.3 ± 1.5	1.6 ± 0.4	<6.6	2.0 ± 1.1	4.2 ± 1.4	4.2 ± 1.4
	1.7 ± 0.3	1.7 ± 0.3	2.3 ± 0.9	1.0 ± 0.3	2.2 ± 1.4	2.8 ± 1.2	1.2 ± 0.6	1.1 ± 0.4
Tailings Average	1.6 ± 0.2	1.6 ± 0.2	3.3 ± 0.8	1.2 ± 0.2	<3.6	2.3 ± 0.7	3.0 ± 0.7	3.4 ± 0.7

a) Picocuries (10^{-12} curies) per gram plus or minus twice the standard deviation based on counting statistics.

TABLE 11. AMBIENT STATION RADON-222 CONCENTRATIONS - OPEN PIT COPPER MINE

		Radon-222 Concentration (nCi/m^3)[a]		
Date	Time	Kaw Avenue	Alpine	Mt. Con
10/14/80	1200-1500	0.63 ± 0.7 (C)[b]	0.53 ± 0.07 (U)[b]	
	1600-1900	<0.07 (U)	0.21 ± 0.06 (C)	0.20 ± 0.06 (C)
	2000-2300	0.28 ± 0.05 (U,D)	0.30 ± 0.07 (C)	0.32 ± 0.06 (C)
10/15/80	0300-0600	1.1 ± 0.1 (U,C)	1.3 ± 0.1 (D,C)	0.32 ± 0.05 (U,C)
	1200-1500	0.44 ± 0.06 (U)	0.22 ± 0.05 (C)	0.20 ± 0.05 (C)
	1600-1900		0.09 ± 0.05 (C)	
10/16/80	0700-1000	0.57 ± 0.04 (NA)	0.69 ± 0.09	0.55 ± 0.04
			0.95 ± 0.09	0.77 ± 0.11
			0.82 ± 0.06 (NA)	0.66 ± 0.06 (NA)
	1200-1500	0.10 ± 0.04 (C)	0.12 ± 0.05 (U)	
	1600-1900	0.16 ± 0.05 (U)	0.08 ± 0.03 (C)	0.23 ± 0.06 (C)
10/17/80	0000-0300	0.81 ± 0.06 (C)	1.2 ± 0.1 (U)	0.83 ± 0.08 (D)
	1200-1500	0.14 ± 0.02 (U)	0.19 ± 0.02 (C)	0.28 ± 0.03 (C)

a) Nanocuries (10^{-9} curies) per cubic meter plus or minus twice the standard deviation based on counting statistics.

b) Upwind (U), downwind (D), or crosswind (C) from the open pit mine, based on hourly average wind observations at Mt. Con site. NA = not available due to recorder failure.

TABLE 12. COPPER MINE CRUSHER AND CONCENTRATOR - RADON-222 MEASUREMENTS

Source	Collected Time	Collected Date	Concentrations (nCi/m^3)[a] Gross	Concentrations (nCi/m^3)[a] Net	Annual Emissions (Ci/Yr)
Primary	1422-1706	10/14/80	0.62 ± 0.08	0.46 ± 0.11	
	0300-0600	10/15/80	0.90 ± 0.09	-0.20 ± 0.13	
	1200-1500	10/17/80[b]	0.66 ± 0.03	0.46 ± 0.08	
	Primary Crusher Average			0.24 ± 0.38	0.22
Secondary	1435-1752	10/14/80	0.45 ± 0.08	0.29 ± 0.11	
	1225-1538	10/15/80	0.26 ± 0.07	0.06 ± 0.10	
	Secondary Crusher Average			0.18 ± 0.16	0.077
	Total for seven stacks				0.50
Truck	1630-1903	10/15/80	0.36 ± 0.06	0.25 ± 0.08	
	1154-1412	10/16/80	0.74 ± 0.06	0.63 ± 0.06	
	1514-1819	10/16/80[b]	0.35 ± 0.03	0.23 ± 0.07	
	Truck Hopper Average			0.37 ± 0.23	0.31
Concentrator	1106-1419	10/14/80[b]	1.1 ± 0.1	0.57 ± 0.12	
	1140-1505	10/15/80[b]	0.45 ± 0.05	0.16 ± 0.14	
	1519-1825	10/15/80	0.25 ± 0.06	0.16 ± 0.14	
	Concentrator Bldg. Ventilator Avg.			0.30 ± 0.24	0.86

a) Nanocuries (10^{-9} curies) per cubic meter plus or minus twice the standard deviation based either on counting statistics or sample variance for source averages.

b) Derived from duplicate samples.

c) 144-hour per week operation.

Radon concentrations and emission rates determined for the stacks and building surveyed are given in Table 12. Each of the sources showed average radon concentrations which were above the ambient levels determined from the ambient stations. The maximum net concentration observed was 0.37 ± 0.23 nCi/m^3 in the truck hopper exhaust. The maximum annual emission rate for a single source was 0.86 Ci/y from the concentrator building. Total radon emissions from the crusher and concentrator operations was 1.9 Ci/y.

Concentrations of uranium-234 and uranium-238 in stack emissions averaged 0.2 pCi/m^3 from the primary crusher and 0.09 pCi/m^3 from the truck hopper. These compare to measured ambient concentrations of about 0.5 fCi/m^3. Annual emissions measured from the primary crusher and truck hopper were less than 1 mCi (Table 13).

TABLE 13. AVERAGE ANNUAL EMISSIONS FROM AN OPEN PIT COPPER MINE

	Radionuclides (mCi/y)[a]							
Source	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Primary Crusher	0.24	0.24	<0.3	0.11	0.89	<1	<0.3	<0.3
Truck Hopper	0.07	0.14	<0.3	0.07	<1	<1	<0.3	<0.3

a) Millicuries (10^{-3} curies) per year, calculated from Method 5 contractor data

Aerodynamic particle size measurements are summarized in Table 14. Since these are samples of comminuted ore it is believed that the radioactivity distribution would be similar. Radioactivity quantities on the samples were too low to measure.

TABLE 14. AERODYNAMIC PARTICLE SIZE DISTRIBUTIONS FROM OPEN PIT COPPER MINE

	Geometric Mean Diameter (μm)	Geometric Standard Deviation (μm)
Truck Hopper	7.8	2.8
Truck Hopper	12.5	4.8
Primary Crusher	5.0	2.4
Primary Crusher	4.8	2.7
Coarse Ore Storage Pile	0.84	7.6
Coarse Ore Storage Pile	0.04	33
Leach Screening	0.025	104
Leach Screening	0.22	14

Measurements of radon emanation rates from the surface of the mine and surrounding areas are summarized in Table 15. Several canisters in the mine were lost due to mining activities, but those that were collected show an increase in emanation rates as a function of depth. This may be real or may result from infiltration of radon from the surrounding air. Radon would be expected in higher concentrations near the bottom of such a pit, whether natural or man-made. The difficulty of sealing canisters to the rocky mine surfaces could have allowed some infiltration. In general, the emanation rate from a rock surface would be less than from soil because of the lower porosity of rock. Radon emanation rates from the area east of the pit are comparable to the reported national average for U.S. soils of 35 pCi/m^2-min (4). The highest radon emanation rate was measured from a reportedly undisturbed soil area northwest of the mine. High radon emanation rates in the area are believed to be due to a combination of extensive underground mining, cracks in the earth structure, and the high mineralization of the area.

TABLE 15. OPEN PIT COPPER MINE RADON EMANATION RATES

Emanation Rates (pCi/m^2-min)[a]		
Mine Pit (In Order of Increasing Depth)	East of Pit (In Order of Increasing Distance)	NW of Pit (In Order of Increasing Distance
2.3	15	
14	25	100
4.5	35	170
26	1.2	120
130	39	24

a) Picocuries (10^{-12} curies) per square meter per minute.

REFERENCES

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